UCRL-JC-152350

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August 29, 2003

Third International Conference on Inertial Fusion Science and Applications, Monterey, California, September 7-12, 2003

This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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TECHNOLOGY ISSUES AND BENEFITS OF A FAST IGNITION POWER PLANT WITH CONE TARGETS*

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ABSTRACT

The use of cone focus, fast ignition targets, either for direct or indirect drive, promises to lower the required driver size and relax the symmetry requirements in IFE power plants. It may also allow use of chamber concepts previously thought infeasible with a laser driver. These benefits will lower the COE and make IFE plants more competitive at smaller size. Their use also raises unique issues that will impact the design and development of power plant subsystems. Cone targets have a significant mass of high Z material whether or not they have a hohlraum and they are not spherically symmetric. This has implications for target injection, tracking and chamber background gas allowable.

I. INTRODUCTION

The fast ignition concept promises to make smaller inertial fusion power plants economically viable because it offers higher target gain at smaller driver size. The importance of driver efficiency and the cost of electricity will be reduced. Fast ignition may also allow: 1) relaxed requirements on target fabrication, 2) reduced capsule drive symmetry, and 3) lower fuel compression energy. High gain with relaxed symmetry raises the possibility of one-sided illumination of indirect drive targets[1,2] and of using thick-liquid-wall chambers.[3] Use of such chambers results in longer-life structures, again reducing the cost of a FI power plant and perhaps shortening and reducing the cost of the development program. Moir reported similar benefits for thick liquid wall chambers using central indirect drive targets with two-sided illumination.[4]

Experiments have shown increased ignitor beam coupling to fast ignition targets if a heavy cone is embedded in one side of the target.[5] The cone serves two functions. First, it prevents the expanding plasma from interfering with the ignitor beams. Second, it helps focus the ignitor beam energy onto a smaller spot.[6] However, the cone also raises some reactor technology issues that are the focus of this paper.

II. CONE FOCUS TARGET DESIGNS

Some cartoons of what cone focus targets might look like are shown in Figure 1.

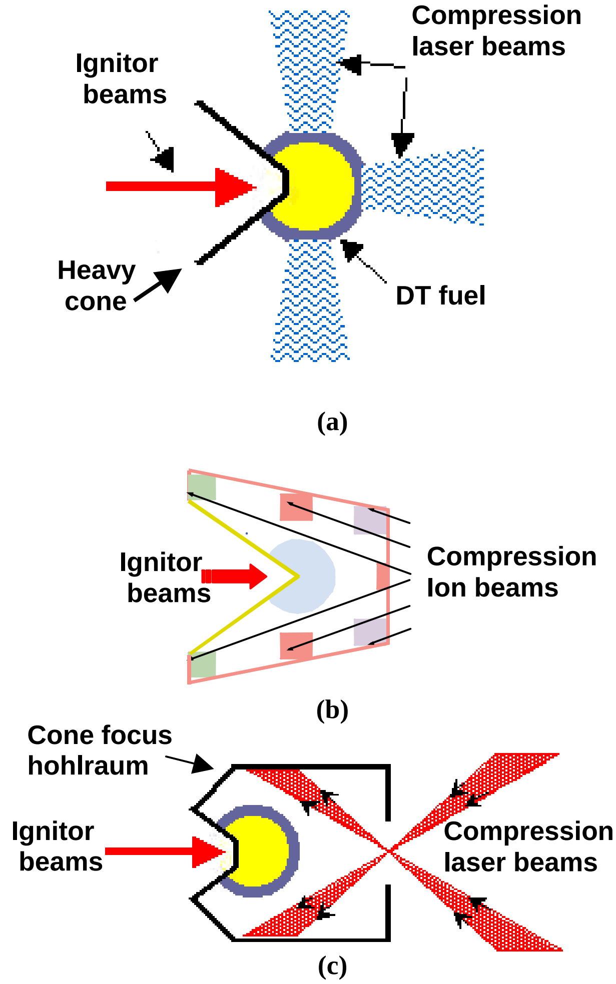

Figure 1. Three types of cone focus targets are shown in (a) Direct laser drive, (b) Indirect heavy ion drive[2], and (c) Indirect laser drive[7].

a. Principal author performed some of this work as a Visiting Professor at the Institute of Laser Engineering, Osaka University.

When a high atomic number cone is added to the direct drive target it will behave, during target handling processes, more like a hohlraum target. The cone must be thick enough not to break up during the implosion of the fuel capsule attached to it. As an upper limit consider 50 Mbar pressure for 15 ns duration. Not allowing the cone to move more than one thickness would require a thickness of about 260 microns of Pb (realistically the cone could move several thicknesses before breakup). It must be long enough that the plasma blow off from the capsule does not get into the line of sight of the ignitor beams. These conservative assumptions lead to a cone length of about 4X the radius of the fuel capsule. This cone would weigh about 0.3 grams, i.e. about the same weight as a typical hohlraum!

On the other hand, when adding a cone to a hohlraum, the cone need only be long enough to connect to the hohlraum, i.e. about 2X the radius of the fuel capsule. This is because the plasma is retarded by the hohlraum. Thus, with the exception of aerodynamic stability, the direct and indirect drive cone focus targets behave similarly during target handling processes.

III. ECONOMIC ADVANTAGES OF USING CONE FOCUS FAST IGNITION TARGETS

We previously showed the potential economic benefits of fast ignition for a laser driven IFE power plant, indicating up to 32% lower cost of electricity (COE).[1] Here we considered what improvement could be made if fast ignition was used for a heavy ion driven power plant. An updated point design for a heavy ion accelerator driven IFE power plant was recently published, and is referred to as the Robust Point Design (RPD) since relatively conservative assumptions were used throughout.[8] Preliminary target physics scaling indicate that the compression driver energy for a FI heavy ion target would be 2.75 MJ compared to 7 MJ for the RPD. Assuming the same ion (Bi, A = 209) and required spot size (~2mm), the driver cost is reduced from ~$2.8 B to $1.5 B (total capital cost), and with less restrictive pulse shaping the number of beams could be reduced from 120 to 48. At a rough estimate of $1000/J, the 150 kJ ignitor laser (50 kJ absorbed in fuel) would add $0.15 B. The COE versus compression driver energy is shown in figure 2 for the ignition distributed radiator (DR) target used in the RPD study (blue dashed line) and for the fast ignition case (red solid line). Design points at a fixed rep-rate of 6 Hz (limited by liquid injection velocity) are indicated by the small circles. The 7 MJ, 6 Hz point is somewhat off optimum for the DR target. While operating at 6 MJ would reduce the COE by ~3%, the corresponding rep-rate of 8 Hz would require a liquid jet injection velocity > 17 m/s, which exceeds our currently assumed limit of 12 m/s based on concerns about damage in the pipes and orifices. The 2.75 MJ, 6 Hz point, however, is right on the cost optimum for fast ignition targets. The cost of electricity in this case is ~5.4 ¢/kWeh, or about 25% lower than the RPD result. Furthermore, if a larger spot size could be accommodated in the design of the FI target, a somewhat lighter ion (Xe, A = 131) could be used which reduces the driver cost to ~$1.2B, with a resulting COE of ~4.9 ¢/kWeh (31% lower than the RPD). Thus, there is significant economic incentive for fast ignition with heavy ion drivers, although it is slightly less than for laser drivers due to the higher efficiency of the accelerator.

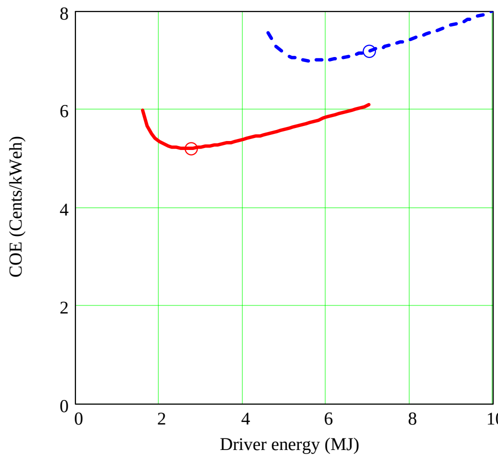

Figure 2. COE vs. driver energy for fast ignition (red/solid) and central ignition (blue/dashed) for ~1.1 GWe net power plants. Design points at fixed 6 Hz are indicated with the small circles.

IV. TARGET INJECTION AND TRACKING ISSUES

Cone focus direct drive targets will behave, during injection and tracking, much more like indirect drive targets than conventional direct drive targets. Injection of the target cone first (see Fig. 3) would be of some benefit because the cone helps protect the cryogenic fuel of the target during injection. Furthermore, the heavier cone target is less vulnerable to chamber turbulence. However, the cone focus direct drive target will have to be spun up to prevent tumbling. Hohlraum injection experiments by Petzoldt found spin rates of 200 rev/s or more prevented tumbling.[9]

The axis of a spinning target will still precess about its direction of travel because of alignment errors during injection. Non-axisymmetric stresses on the cryogenic fuel will develop. The same experiments by Petzoldt[9] found that the precession angle was less than 9 milliradians with spin rates above 200 rev/s. This should be sufficiently small that the stresses during injection can be handled. However, to spin this target up to this spin rate in the injector may cause more extreme stresses and it is possible that a sabot must be used.

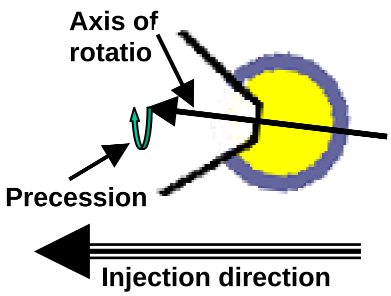

Figure 3. The axis of rotation of the cone target will precess about its direction of travel

In considering chamber drag forces and the effect that they might have on tracking requirements, Petzoldt[10] found that the displacements induced by drag on conventional direct drive targets in gas protected chambers could require tracking to within a few tens of centimeters of the center. The cone direct drive target should be better off. While the drag force is four times that for a target without a cone, the mass is 150 times larger so the displacement should be much smaller and tracking requirements reduced. Furthermore, with the center of mass so far forward, these targets seem to be inherently unstable aerodynamically. These issues require further analysis and demonstration.

For the indirect drive targets, either for a heavy ion driver or for a laser driver, the presence of the cone does not significantly alter the dynamics of injection and tracking. However, since the center of mass is further back, the targets are more stable than the direct drive cone targets.

V. USE OF THICK LIQUID WALL CHAMBER CONCEPTS FOR FAST IGNITION

Moir has illuminated the benefits of using thick liquid wall chamber concepts like HYLIFE II for heavy ion driven central ignition targets.[4] In the cases he examined, ion beams came from both ends.

The cone focus heavy ion target shown in Fig. 1b, on the other hand, have ion beams from one end and the laser ignitor beams from the other. Section III of this paper showed the economic benefit of using this concept compared with the double-ended illumination of central ignition targets.

Consideration of double-ended laser driven hohlraum targets for inertial fusion power plants has fallen out of favor in recent years because internal symmetry requires so many illumination angles[11] that thick liquid wall chambers could not be used. Without that advantage there seemed to be no overall advantage to laser hohlraum targets for a power plant if the direct drive targets give the high gains calculated.

However, the cone-focus laser indirect-drive target of figure 1c may revive interest. The fact that symmetry requirements can be relaxed for the compression beams may mean that the laser illumination can come from one end and from a smaller number of angles. While this has not yet been calculated, if the maximum cone angle for the illumination beams is small enough, then chamber concepts like HYLIFE II can once again be considered for laser indirect drive.

Use of the HYLIFE II concept would reduce the size and cost of the containment building compared to the Sombrero concept, even if grazing incidence metal mirrors were used for the final optics of the compression beams. It reduces operating costs because of the smaller waste stream from neutron-activated material. It eliminates the requirement to periodically replace the first structural wall, thereby increasing availability and reducing O&M costs. Finally, the use of a HYLIFE II concept would eliminate the need for a fusion neutron materials development facility, thereby reducing the time and cost of the development path.

Determining whether the single-sided laser target of Fig. 1c can give sufficient gain at low drive energy and determining the minimum cone angles for illumination should be a high priority of fast ignition target designers. Because cone targets seem to give more than enough gain at low drive energy, some gain can be forfeited for the advantages of using the HYLIFE II chamber.

VI. PROPAGATION OF IGNITOR BEAMS THROUGH RESIDUAL GASES OF THE CHAMBER

The cone of the fast ignitor target can be made long enough to prevent blow-off from the compression laser from entering the beam path of the ignitor beams, eliminating the need for the ignitor beams to bore through the blow-off plasma. The beams must, however, still penetrate whatever background vapor fills the fusion chamber. For the thick liquid wall chamber, this will be residual vapor from the molten salt that is vaporized on each shot. At an operating temperature of ~600 C, the vapor pressure of the Li_2BeF_4 molten salt is ~2×10^{-6} atm and is dominated by BeF_2. If this material was completely ionized, the electron density would be ~3×10[14]/cm[3]. Thus, even if the flibe only returns to within a couple orders of magnitude of its equilibrium vapor pressure between shots, the chamber electron density will be many orders of magnitude below the critical density for 1 um ignitor laser ($\sim 10^{21}/cm^3$). For direct drive laser chambers, a 10-20 mtorr background gas (typically Xe) is used to reduce the x-ray load on the chamber first wall. This gives an atom density of $<10^{15}/cm^3$ and a potential electron density an order of magnitude higher (depending on ionization level), which is also many orders of magnitude below the laser critical density. Although detailed propagation calculations have not been done for the extremely short and intense ignitor beams ($\sim 10^{19}$–10^{20} W/cm^2 near focus), it is expected that beam instabilities such as Stimulated Brillion and Simulated Raman scattering will not be a problem at these low background densities.[12]

VII. THE EFFECT OF DUDS

Mima has suggested that the dud rate for cone focus targets may be larger than for central ignition targets.[13] The compression may be much more turbulent if the illumination symmetry is relaxed. Since the ignitor beams are of very short duration, there may be an increased probability that the ignitor beams will hit a lower density spot in the target. This would cause a larger dud rate.

The economic model for laser driven plants was altered to illuminate the consequences of a higher dud rate. Gain curves were multiplied by 0.6 to account for a dud rate of up to 40%. After re-optimizing the COE it was found that the overall economic penalty was only 8% even though the laser driver size had to be increased by 45%. This was because the driver cost is no longer an overwhelming factor.

A larger concern with cone targets is the damage from debris and shrapnel for a dud target. For a hohlraum target shrapnel and debris from a cone target will be about the same as for a central ignition hohlraum target. However, a dud direct drive cone target presents a more difficult issue as shown in Figure 4.

Imagine the capsule in figure 1a vaporized by the compression driver. The high Z mass is all on one side of the compressed gas of the fuel capsule. If the target does not ignite the cone itself will not be vaporized except at the very tip. Thus the rest of the cone will be accelerated by the ball of high pressure gas. It will likely break up and be accelerated directly toward the final optics of the ignitor beams. Calculations of the size and direction of the shrapnel will be very important.

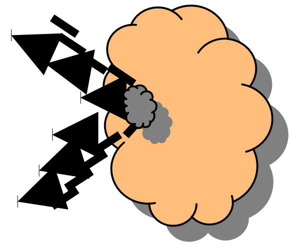

Figure 4. A cone focus, direct drive target that is a dud will propel shrapnel toward the ignitor final optics.

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* Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract W-7405-ENG-48.